Effects of The Environmental Uncertainty on Matched-Field Source Localization in Terms of Parameter Coupling

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By

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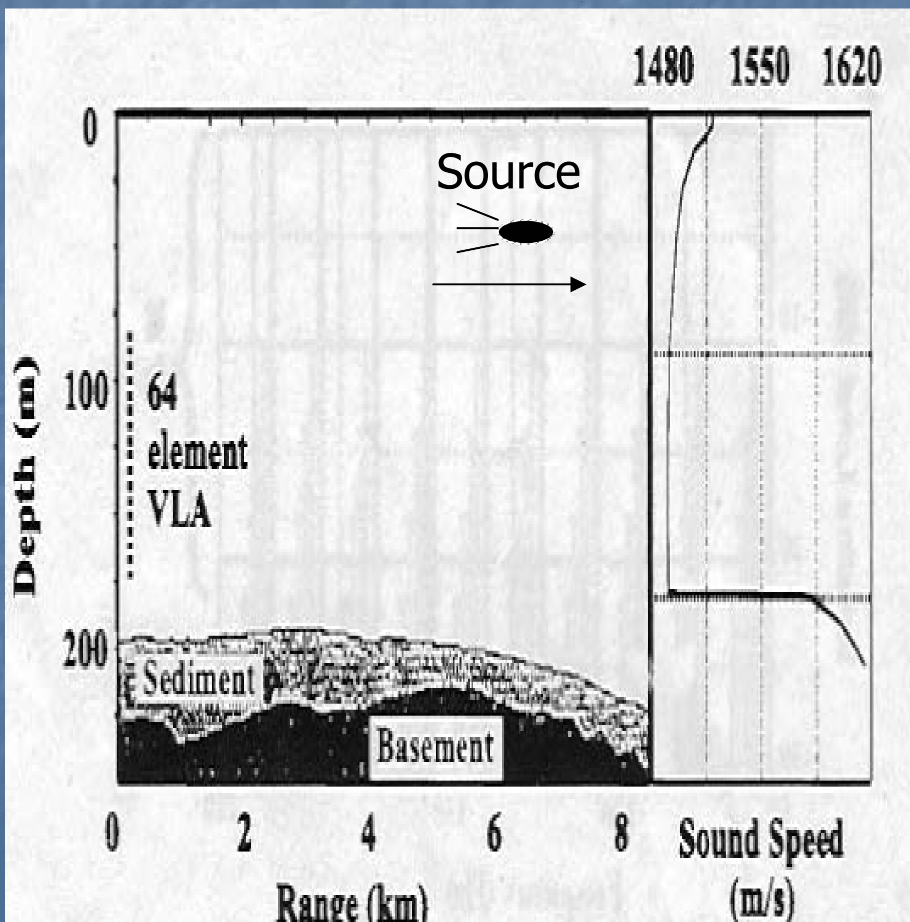
Outline

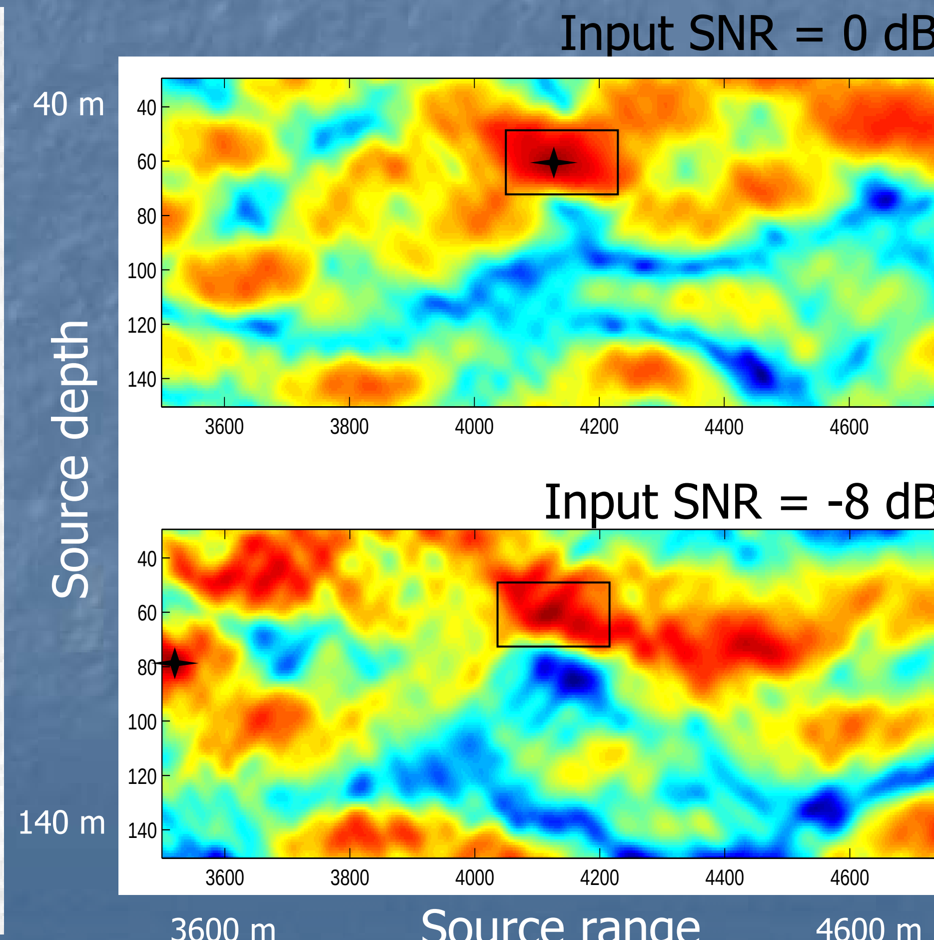
- Background on matched-field source localization
  - Matched-field concept
  - Typical performance behaviors
- Effects of adding additional parameters
  - Weakly coupled parameter
  - Strongly coupled parameter
  - Mutual coupling between environmental parameters
- Cramer-Rao bound criterion for acoustic parameterization
  - Strategy for the Uncertainty DRI
- System-orthogonal function for sound velocity profile uncertainty
  - Demonstration example

Matched-field parameter estimation works by matching the measured signal field with the modeled full-field replica

Shallow Water Evaluation Cell Experiments
(SWellEX, Booth, *et al.*, 1996)



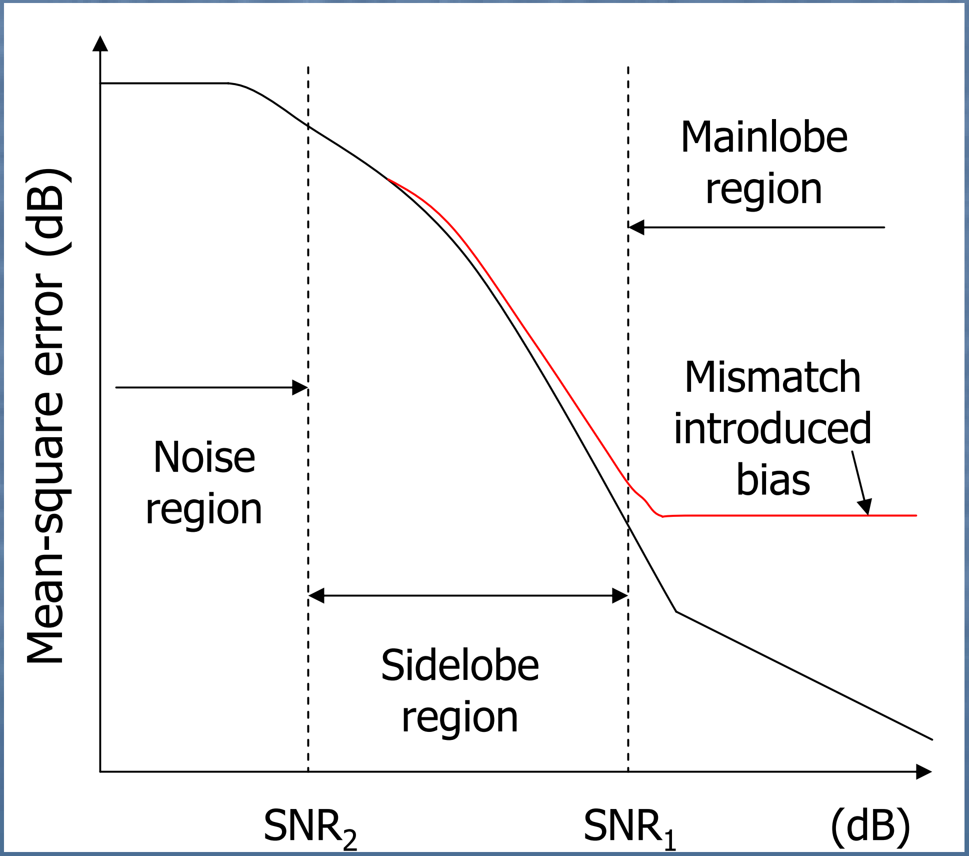
Source localization ambiguity surface



Matched-field performance often shows a strong sensitivity to environmental uncertainty/mismatch as well as a threshold behavior due to the ambiguity sidelobe effect

Performance analysis tools

- Statistical data model
- Mean-square error bound
- Cramer-Rao bound
  - Good at high signal-to-noise ratio (SNR)
- Ziv-Zakai bound
  - Good at all SNRs
  - Computationally intensive
- Modified Ziv-Zakai bound (Xu and Baggeroer)
  - Include the mismatch effect
- Bayesian framework
  - Random parameters



Environmental uncertainty can be included as a random parameter set estimated together with the source parameters

- Effects of adding additional parameters depend on the parameter coupling
- Parameter coupling describes how the error in the estimation of one parameter correlates with the error in the estimation of another parameter
- Typical tools analyzing the coupling
  - Mainlobe shape of the ambiguity function
  - Cramer-Rao error covariance matrix

$$E\left[\left(\hat{\theta}-\theta\right)\left(\hat{\theta}-\theta\right)^T\right]=\begin{bmatrix} \varepsilon_1^2 & \varepsilon_{12} & \cdots & \cdots & \varepsilon_{1N} \\ \varepsilon_{12} & \varepsilon_2^2 & & & \vdots \\ \vdots & & \ddots & & \vdots \\ \vdots & & & \ddots & \vdots \\ \varepsilon_{1N} & \cdots & \cdots & \cdots & \varepsilon_N^2 \end{bmatrix}$$

θ

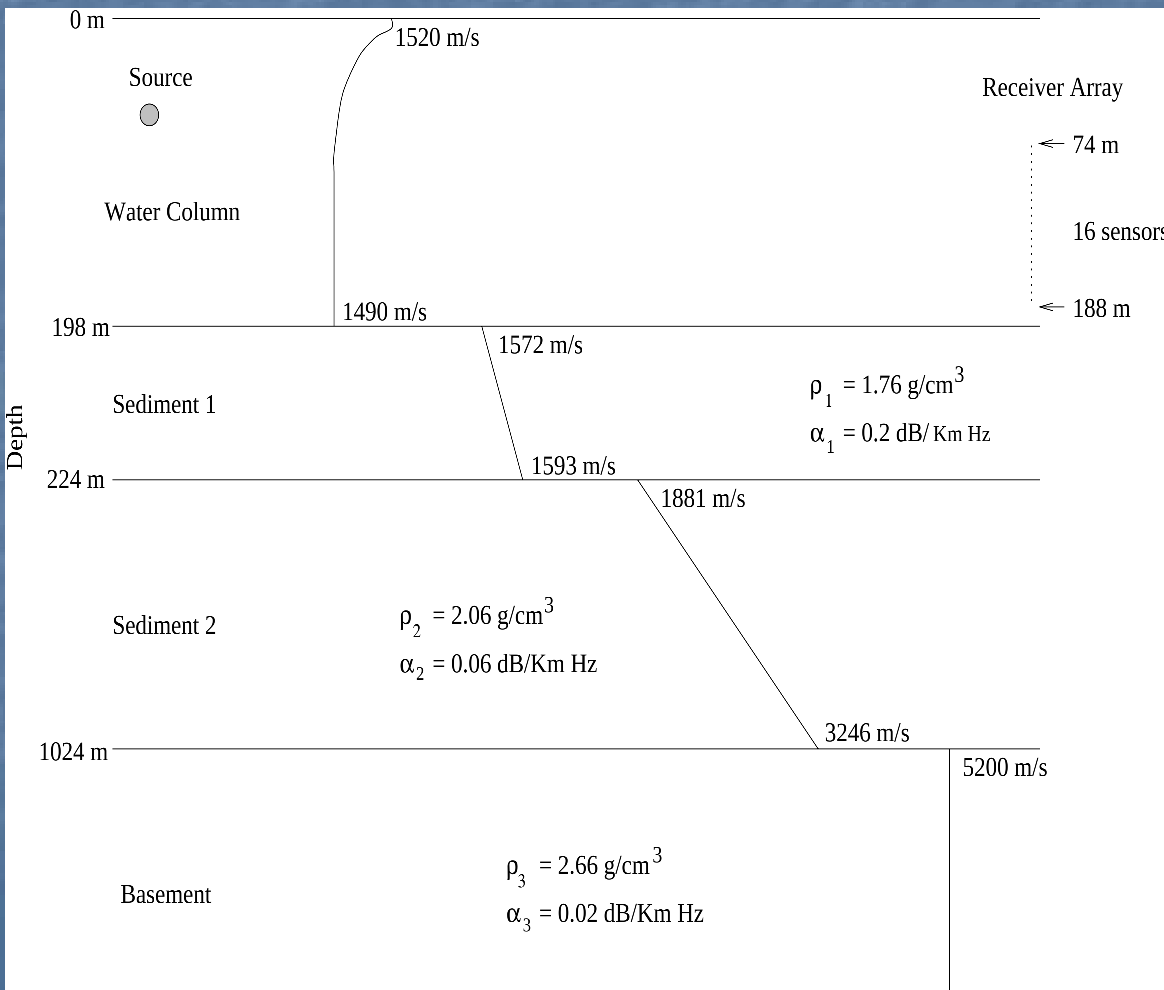
Unknown parameter set

$\hat{\theta}$

Parameter estimate

Parameter-dependences of the acoustic field often demonstrate strong mutual coupling due to the underlying physics

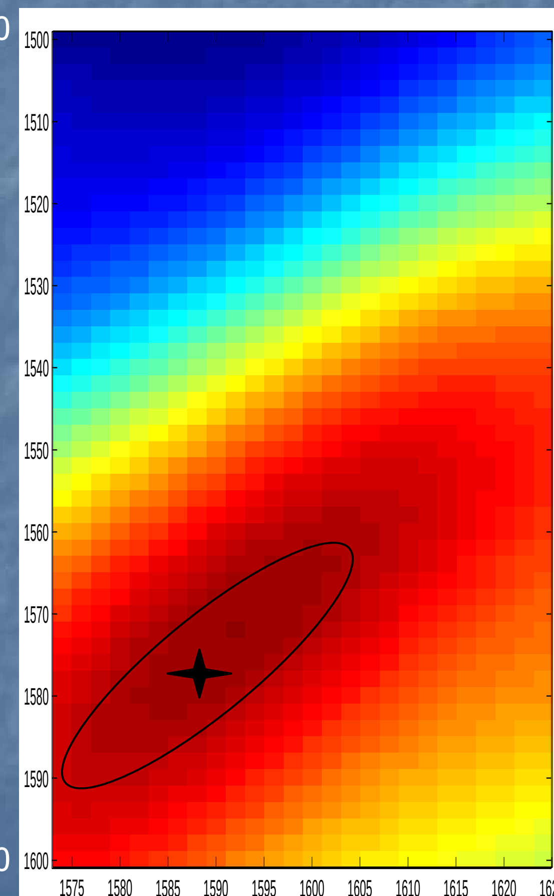
Example environmental model in SWellEX-3



Ambiguity surface

1500 m/s

Sediment top wave speed



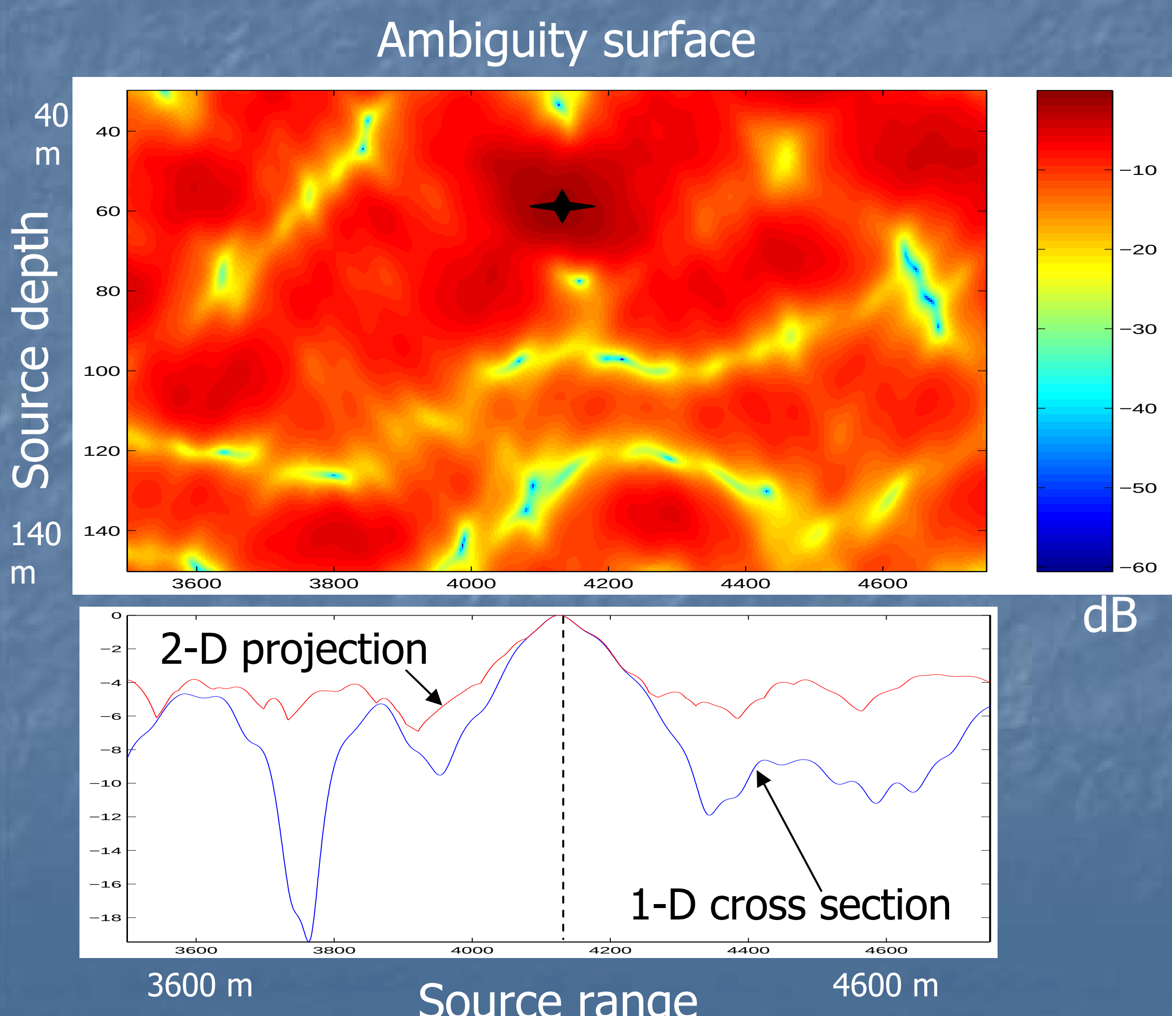
1600 m/s

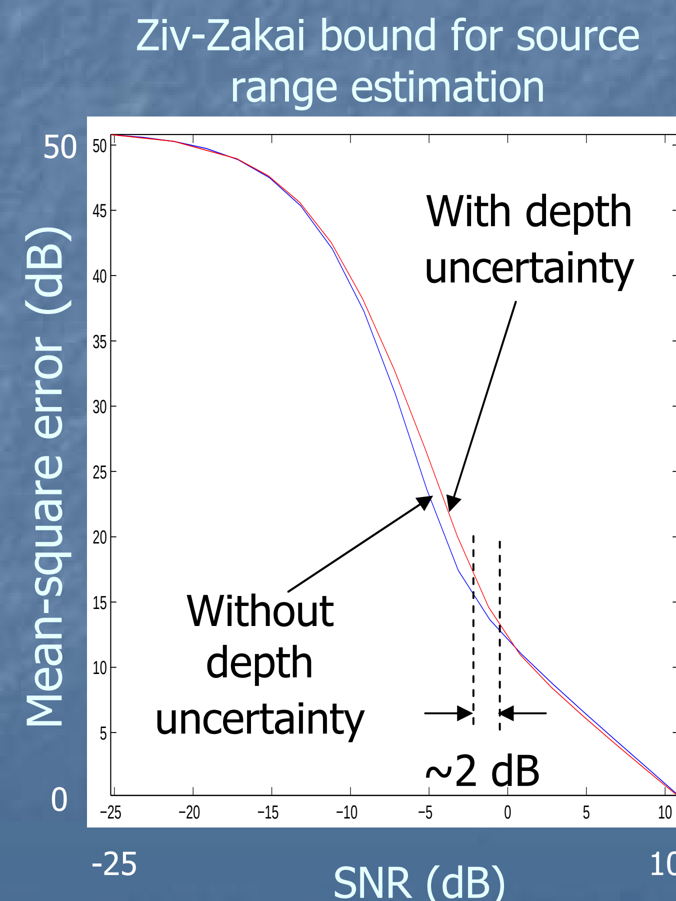
1575 m/s

1625 m/s

Sediment bottom wave speed

Adding a weakly coupled parameter doesn't degrade the high-SNR performance but could increase the threshold SNR due to the added sidelobe ambiguity

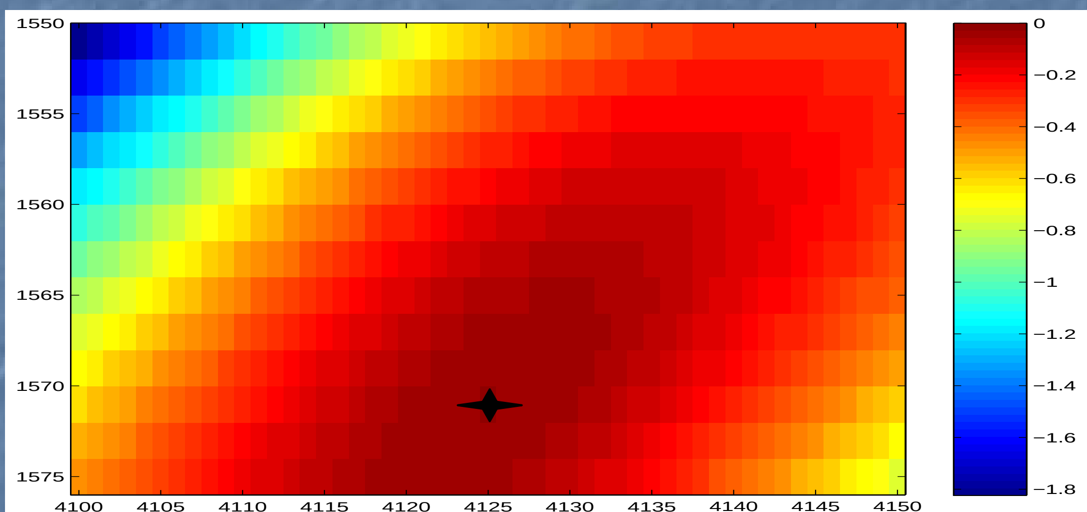




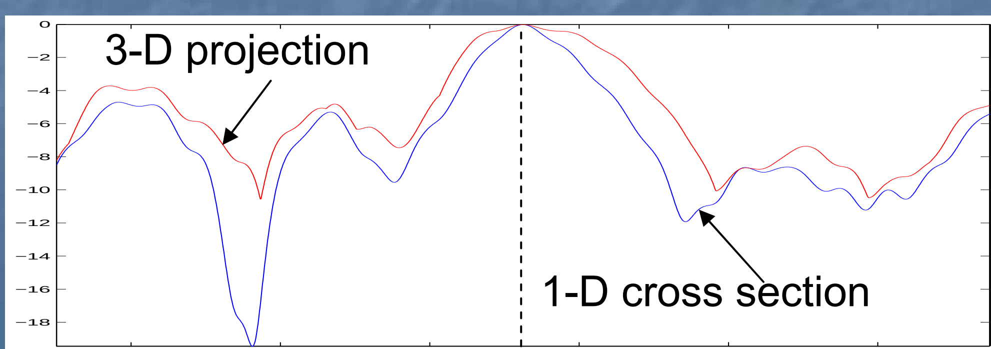
Adding a strongly coupled parameter degrades the high-SNR performance due to the added mainlobe ambiguity but the sidelobe threshold may not be increased

Ambiguity surface

Sediment top wave-speed (m/s)



dB



3600 m

4600 m

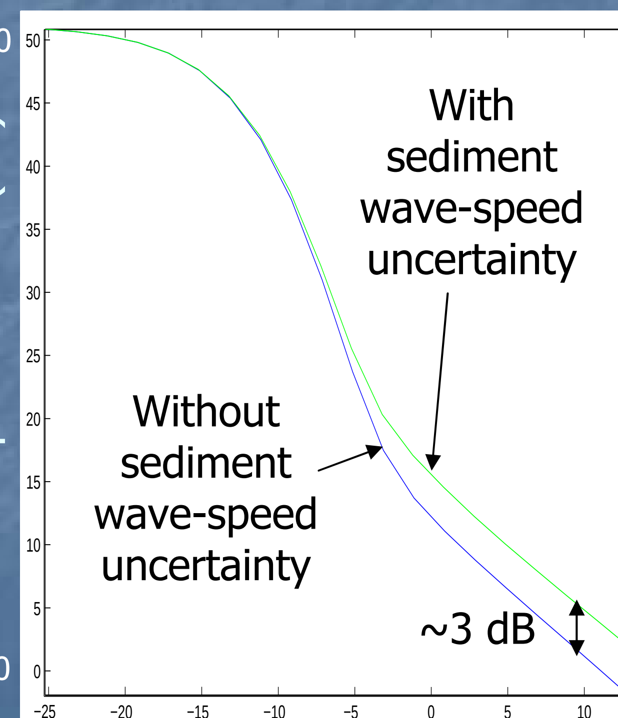
Source range

Ziv-Zakai bound for source range estimation

Mean-square error (dB)

50

0



-25

10

SNR (dB)

A compact set of environmental parameters, mutually decoupled but coupled to source localization is desired for the Uncertainty DRI

- Ignoring the environmental uncertainty could introduce significant environmental mismatch, and thus serious bias in source localization
- AREA is to improve sonar performance prediction by capturing dominant environmental uncertainty under operational constraints
  - Exploit the coupling between the environmental parameter set and the source parameter set
- System response-decoupled environmental representation is desired:
  - Reduce the degrees of freedom
  - Make possible investigation of the relative significance of the individual parameters
  - Simplify the design of optimal adaptive sampling of environment
- Cramer-Rao bound matrix provides a framework to develop acoustic parameterization for the Uncertainty DRI

A new set of orthonormal functions representing the sound velocity uncertainty and decoupling the expansion coefficients in system response has been derived

- Source range estimation with sound velocity profile uncertainty
  - Range: r; Depth: z
  - SVP:

    $c(z) = c_0(z) + \Sigma\, g_l\, \psi_l(z)$

    $c_0(z)$: mean profile

    $\psi_l(z)$: arbitrary orthonormal basis

    $\underline{g}=\{g_1,\ldots,g_L\}$: coefficients

    Covariance matrix: R_c
- Traditional EOFs are decoupled in regard to the SVP statistics but coupled in regard to system response
- Densely populated array spanning the entire water column + Perturbation approximation + Random Gaussian signal model
- CRB matrix

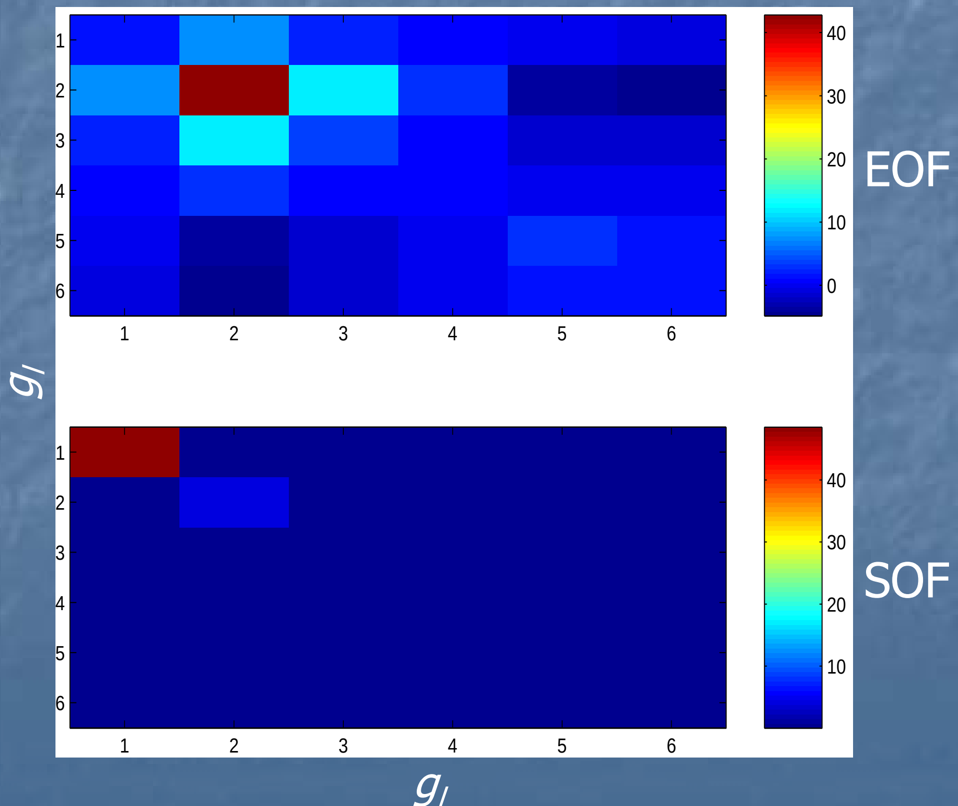
$$\begin{bmatrix} CRB^{r}_{1\times 1} & CRB^{r\underline{g}}_{1\times L} \\ CRB^{\underline{g}r}_{L\times 1} & CRB^{\underline{g}\underline{g}}_{L\times L} \end{bmatrix}$$

- Robust algorithm: $CRB^{\underline{g}r} \rightarrow \underline{0}$
- AREA: $CRB^{\underline{g}r} \rightarrow \underline{1}$
- Decoupled parameter set: $CRB^{\underline{g}\underline{g}}$ is diagonal

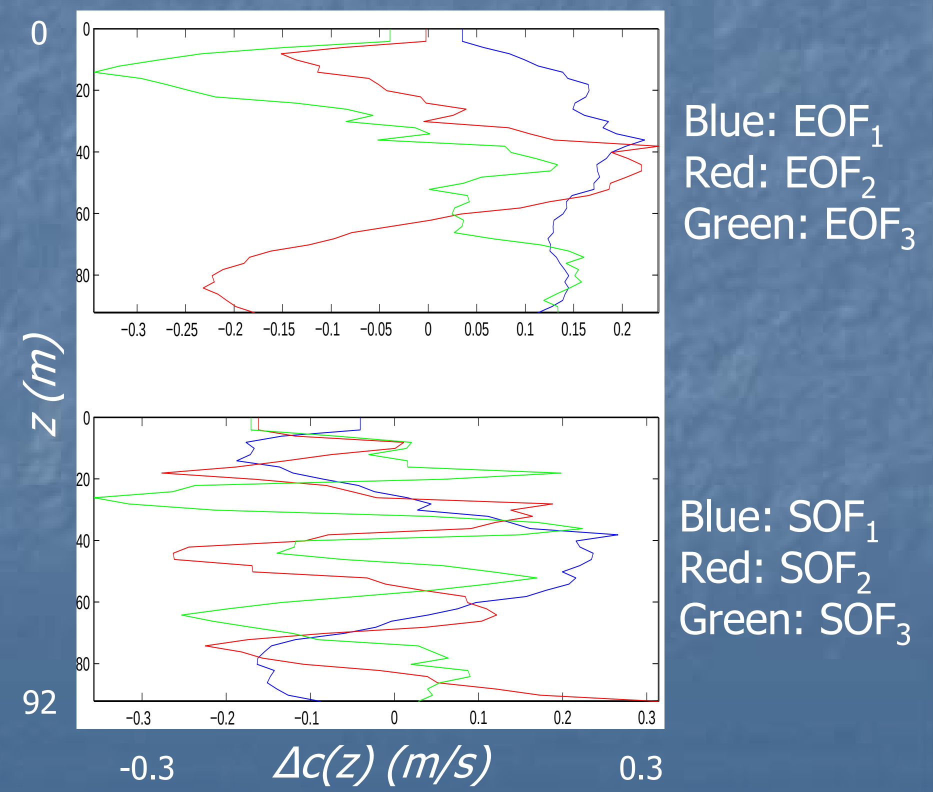
The new set of system-orthogonal basis functions depends on the statistics of the sound speed uncertainty, the sound waveguide propagation property, and the SNR in measurements

Isovelocity channel + Shelf Break Primer SVP statistics (Gopu Potty *et al.*, 2000)

CRB matrix for the first 6 SVP coefficients



Input SNR = 0 dB



AREA - MIT DRI
Future Research Plan

- Continue to develop optimal acoustic parameterization
  - Further derivation based on the CRB matrix
  - Generalization to range-dependent scenarios
  - Volumetric distributed array
  - Applications
- AREA system concept simulation
- Continue to develop consistent Acoustic Data Assimilation (ADA) concept in collaboration with HOPS team
- Perform OSSEs in collaboration with other DRI teams
  - 4-D HOPS forecasts from PRIMER and ASCOT01 experiments
  - Geophysical databases and in-situ measurements